

# EuroSTRATAFORM: Three-Dimensional, Moving-Boundary, Integrated-Morphodynamic Models of Sedimentation on Continental Margins

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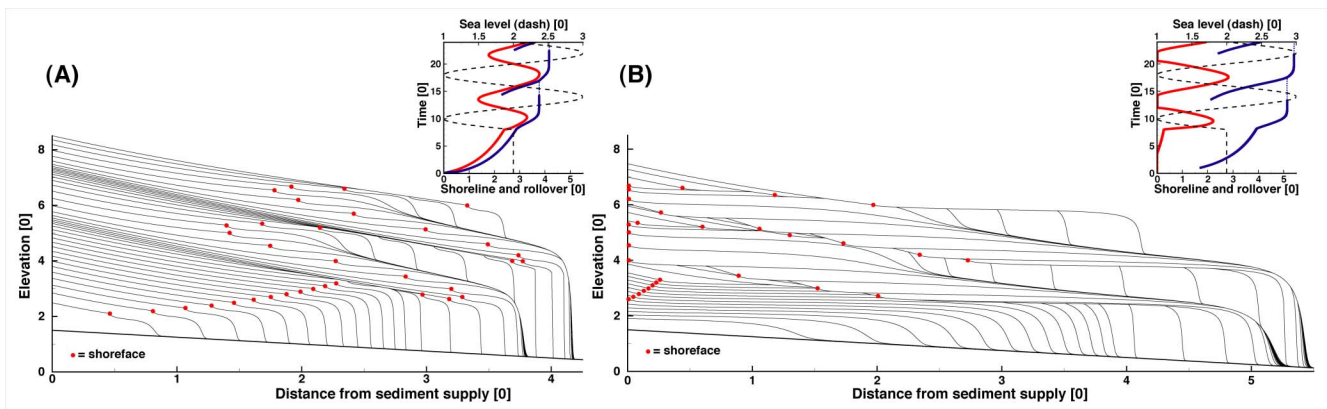
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## LONG-TERM GOALS

My long-term goal is to develop moving-boundary, morphodynamic models of continental-margin response to high-amplitude, late-Quaternary changes in sea level (Task **D4**).

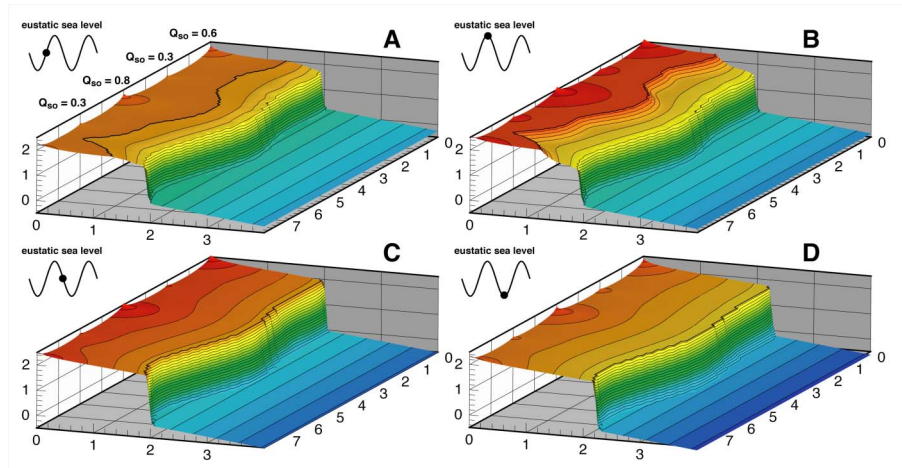


**Figure 1. Cross-sectional model of continental-margin response to high-amplitude fluctuations in eustatic sea level. The panels represent (A) flood- and (B) storm-dominated margins. Large panels show stratigraphic architecture resulting from two sea-level cycles superimposed on steady background subsidence. Red circles denote shoreface location. Stratal spacing:  $\Delta t = 0.6$ . Insets show eustatic sea level (dashed) and the evolution of the shoreline (red) and clinoform rollover (blue).**

## OBJECTIVES

1. Quantify, in two and three dimensions, how the relative importance of fluvial input and basin energetics controls (1) sediment partitioning between the subaerial (fluvial) and subaqueous environments, (2) margin morphology, and (3) the stratigraphic response to high-amplitude fluctuations in eustatic sea level. This partitioning controls the relative motion of the shoreline and the clinoform rollover and has important stratigraphic implications.

2. Apply my three-dimensional morphodynamic model to the Adriatic margin and quantify, at first order, the morphologic and stratigraphic response to late-Quaternary sea-level fluctuations.
3. Analyze, in two dimensions, how coastal prisms respond to late-Quaternary sea level fall, with emphasis on the time-transgressive nature of fluvial erosion, i.e. sequence-boundary evolution.
4. Explore methodologies for incorporating floodplain dynamics into fluvial morphodynamics.



**Figure 2. Three-dimensional morphodynamic model of continental-margin response to a single, high-amplitude eustatic cycle superimposed on steady background subsidence. Panels show margin morphology at (A) maximum rate of rise, (B) highstand, (C) maximum rate of fall, and (D) lowstand in sea level. Warmer colors indicate higher elevations. Bold trace delineates shoreline. Margin characterized by four sediment point sources and relatively large and frequent terrestrial floods. Compare with Figure 3.**

## APPROACH

1. Continued development (with input from co-PIs Lincoln Pratson, Chris Paola, Juan Fedeles, and Mike Steckler) of my three-dimensional morphodynamic model of compound-clinoform evolution in response to subsidence and fluctuations in eustatic sea level.
2. Extended my moving-boundary model (Swenson et al., 2000) of fluviodeltaic sedimentation to (1) treat both the shoreline and the upstream boundary (alluvial-basement transition) as moving boundaries and (2) track accurately through time the spatial extent of fluvial erosion.

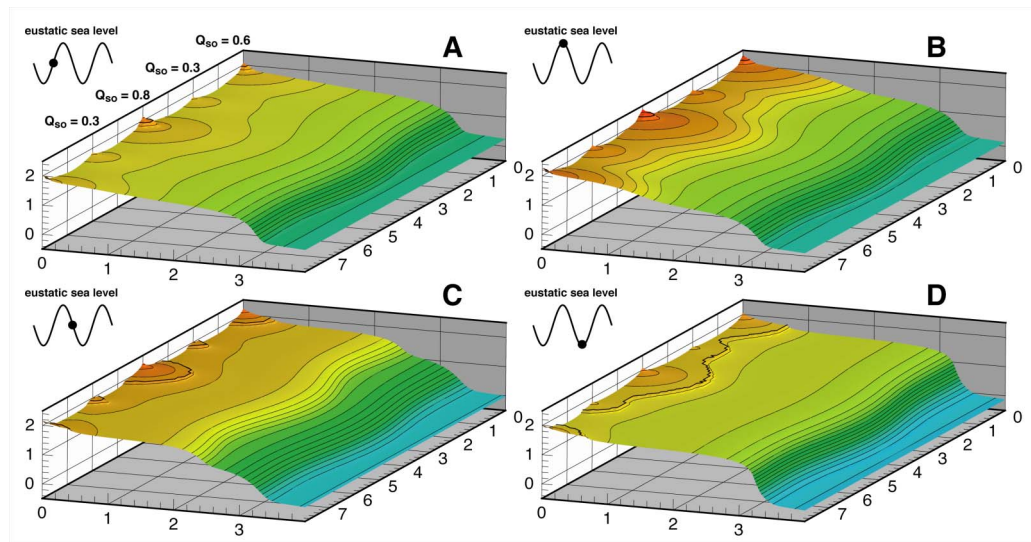
## WORK COMPLETED

1. I continued to develop my three-dimensional, moving-boundary model of compound-clinoform morphodynamics. Fluvial morphodynamics is diffusive; shallow-marine morphodynamics obeys a non-linear advection-diffusion equation (Coco, 1999; Swenson et al., 2003). The fluvial and shallow-marine environments communicate across the surf zone, which I collapse to a shock and treat as a

moving boundary. I employ a fixed-grid, enthalpy-based solution technique (e.g., Voller and Cross, 1981; Crank, 1984). I applied the model to objectives 1 and 2.

2. I modified/extended my cross-sectional, moving-boundary theory for fluviodeltaic sedimentation (Swenson et al., 2000) to model coastal-prism response to late-Quaternary sea level (Objective 3).

3. I worked with Juan Fedeles and Mike Steckler to model floodplain dynamics at a level consistent with the level of sophistication in diffusive fluvial morphodynamics. (Objective 4.)



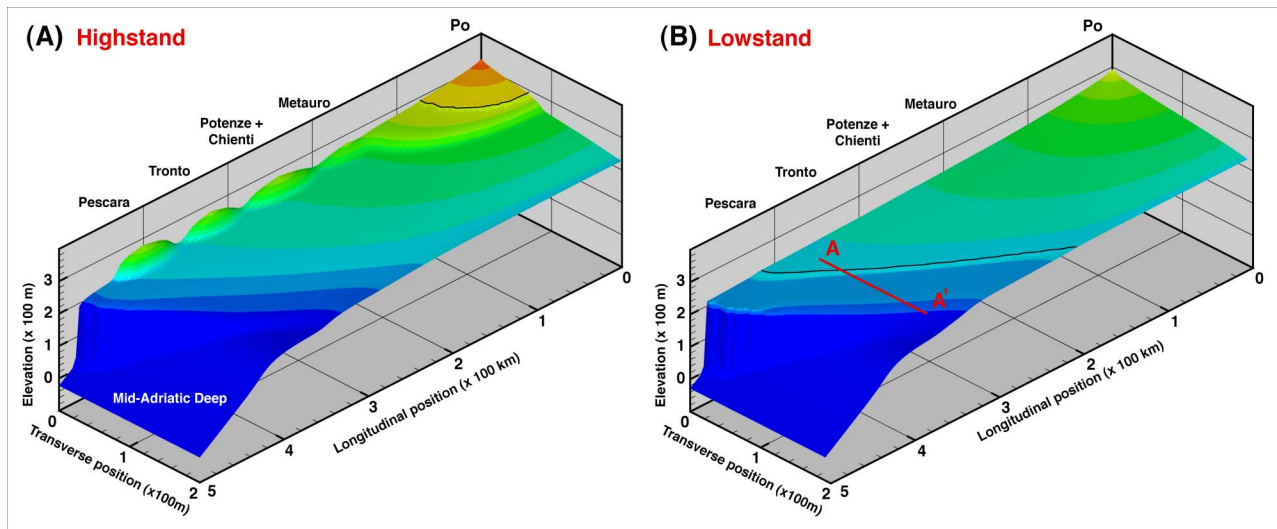
**Figure 3. Three-dimensional morphodynamic model of continental-margin response to a single, high-amplitude eustatic cycle superimposed on steady background subsidence. Compare with Figure 2.**

## RESULTS

1. Modest differences in the magnitudes and frequencies of terrestrial floods and coastal storms generate significantly different stratigraphic responses to sea level cycling. Figure 1 shows a pair of stratigraphic sequences, each arising from two sea-level cycles superimposed on steady subsidence. The lower sequence geometry (Fig. 1B) reflects a two-fold increase in both the frequency and magnitude of coastal storms relative to the upper sequence (Fig. 1A). Less frequent coastal storms, which increase the relative importance of fluvial input, decrease relative motion between shoreline and rollover and limit the spatial extent of fluvial erosion during sea level fall. The resultant sequence (Fig. 1A) displays spatially restricted sequence boundaries and a transgressive systems tract dominated by fluvial facies. In contrast, increasing the frequency of coastal storms increases the relative importance of shallow-marine sedimentation, which allows large-amplitude motion between the shoreline and clinoform rollover and widespread erosion during both sea level fall and rise. The corresponding sequence geometry (Fig. 1B) shows extensive fluvial erosion during sea level fall and transgressive erosion during the rise. The transgressive systems tract consists primarily of shallow-marine strata.

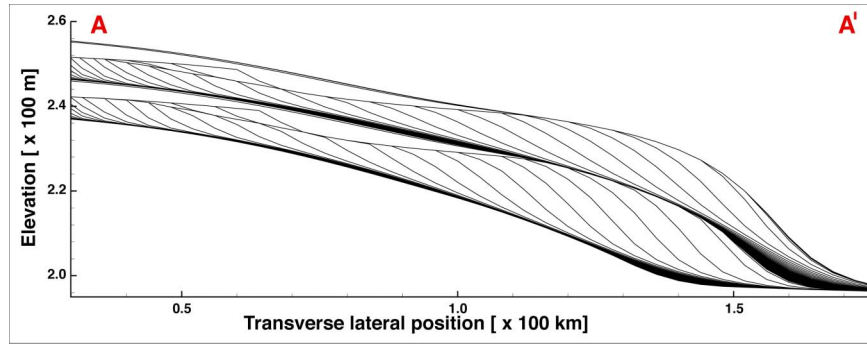
2. Continental-margin morphology varies significantly during sea level cycling. Figure 2 shows the morphologic response of a continental margin, fed by four point sources of differing intensities, to a single sea-level cycle. Note the development of compound clinoforms and their impact on the three-dimensionality of the margin. The active clinoform rollover is abandoned during rapid sea level rise, leaving a sediment-starved subaqueous topset (Fig. 2A). Renewed progradation near highstand generates a pair of compound clinoforms with actively prograding rollovers separating regressive shorelines from the relict shelf edge (Figs. 2B and 2C). Falling sea level drives rapid expansion of the fluvial systems, rejuvenation of the relict shelf edge by the active delta, and an increase in foreset gradient (Fig. 2D). Clinoform interference is strongest during sea level fall and lowstand, rendering the margin largely two-dimensional; in contrast, the margin is strongly three-dimensional near highstand.

3. The three-dimensional morphologic response of margins to sea level cycling is sensitive to the relative importance of fluvial input and basin energetics. Figure 3 shows the morphology of a continental margin with allogenic controls identical to those of the margin in Figure 2, but with twice the magnitude and frequency of coastal storms. Increased “storminess” increases sediment partitioning to the shallow-marine environment, which increases the widths of the subaqueous deltas and allows large-amplitude motion between the shoreline and clinoform rollover.



**Figure 4. Three-dimensional morphodynamic modeling of Adriatic-margin response to late-Quaternary sea-level change. (A) Highstand and (B) lowstand margin morphology; warmer colors reflect higher elevations. Note development of subaqueous clinoform complex on the Apennine coast during sea-level highstand in (A). Bold curves denote shoreline.**

4. On the Adriatic margin, high-amplitude eustatic cycles affected patterns of sediment dispersal in the late Quaternary (Fig. 4). At highstand, e.g. the Holocene, clinoform progradation was dominantly normal to the long axis of the margin (Fig. 4A). At lowstand, the direction of clinoform progradation was parallel to the long axis of the margin (Fig. 4B). The resultant stratigraphic sequences (Fig. 5) reflect this shift in transport direction.

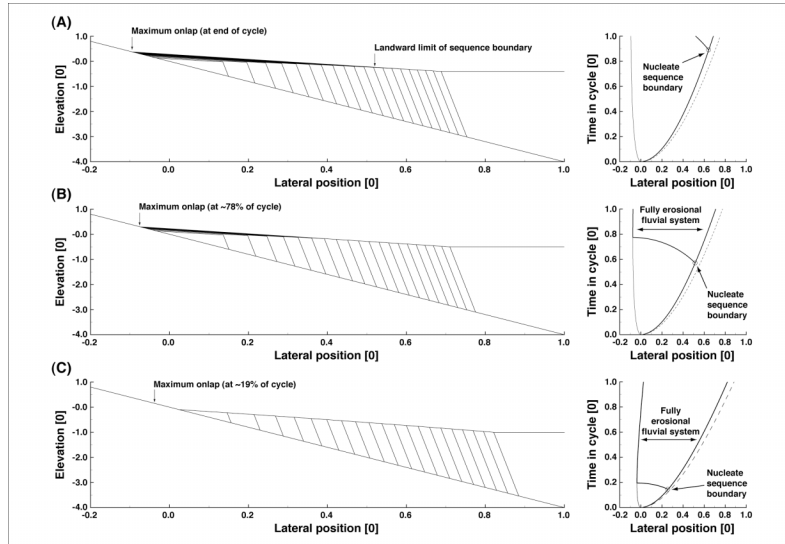


**Figure 5. Stratigraphic response of the subsiding Adriatic margin to two cycles of late-Quaternary eustatic forcing. Cross section shown in Figure 4(B). Stratal spacing is 5 ka.**

5. Coastal-prism response to late-Quaternary sea-level fall is very sensitive to the rate of change in dimensionless sea level  $(dR_{sl}/dt)^*$ , which is the ratio of the rate of fall in relative sea level,  $dR_{sl}/dt$ , to the characteristic sedimentation rate,  $q_{so}/\Lambda$ , where  $q_{so}$  is sediment supply and  $\Lambda$  is shelf length. Figure 6 shows coastal-prism response to a narrow range of  $(dR_{sl}/dt)^*$  values that would characterize many modern fluviodeltaic settings, e.g. the Po River delta.

6. Coastal-prism response to falling sea level displays three evolutionary phases. The prism first expands landward and seaward by coastal onlap and shoreline regression, respectively. Despite falling sea level, the fluvial system, including the shoreline, remains depositional. With lengthening, more sediment is sequestered in the fluvial system, reducing the sediment flux at the shoreline. If  $(dR_{sl}/dt)^*$  is sufficiently large, then the decay in shoreline sediment supply eventually drives the shoreline into an erosional mode, signaling the beginning of the second phase, in which a zone of fluvial erosion expands landward and seaward, tracking the regressive shoreline. The coastal prism continues to grow via fluvial sedimentation landward of the upstream limit of fluvial erosion and deposition on the delta foreset. The third evolutionary phase begins when fluvial incision reaches the alluvial-basement transition. If this occurs, the fluvial system is everywhere erosional for the duration of the fall and the coastal prism migrates seaward via coastal offlap and foreset sedimentation (Figs. 6B and 6C).





**Figure 6. Stratigraphic response of coastal prisms to late-Quaternary eustatic fall with (A)  $(dR_{sl}/dt)^* = 0.4$ , (B)  $(dR_{sl}/dt)^* = 0.5$ , and (C)  $(dR_{sl}/dt)^* = 1.0$ . Each panel shows the stratigraphic architecture of the coastal prism and the associated trajectories of the alluvial-basement transition (thin, solid curve), the shoreline (bold, solid curve), and the delta toe (dashed curve). Open circle on the shoreline trajectory denotes onset of fluvial incision, i.e. nucleation of the sequence boundary. Landward-propagating trajectory emanating from open circle is upstream limit of fluvial erosion.**

7. Sequence-boundary formation in late-Quaternary coastal prisms is strongly time-transgressive and depends sensitively on  $(dR_{sl}/dt)^*$ . The onset of sequence-boundary formation and the upstream extent of fluvial erosion can vary greatly between fluviodeltaic systems, i.e. each system “sees” the eustatic signal differently. Some of the time-transgressive behavior shown in Figure 6 has been documented in physical experiments (Heller et al., 2001) and field studies (Plint et al., 2001; Tornqvist et al., 2003). However, sequence-stratigraphic models, e.g. Posamentier et al. (1988), which use sequence boundaries for stratigraphic correlation and sea-level reconstructions, do not capture such behavior.

## IMPACT/APPLICATIONS

Model results quantify how clinoforms, which are the building blocks of stratigraphic sequences (e.g., Pirmez et al., 1998; Steckler et al., 1999), and continental-margin geometries depend fundamentally on terrestrial-flood and coastal-storm parameters.

## RELATED PROJECTS

I continue to work closely with Chris Paola (UMN) on testing fundamental predictions of stratigraphic theory in physical experiments. In addition, I work with Brad Murray (Duke Univ.) on modeling nearshore processes and with Tetsuji Muto (Nagasaki Univ.) on theory and flume experiments related to fluviodeltaic response to late-Quaternary sea level.

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Swenson, J.B., Paola, C., Pratson, L., Voller, V.R., and Murray, A.B., Fluvial and marine controls on combined subaerial and subaqueous delta progradation: Morphodynamic modeling of compound-clinoform development, submitted to *Journal of Geophysical Research—Earth Surface*, in review.

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